CONTRIBUTED PAPER

Proposed Array-Based Deep Space Network for NASA

Linked, centrally controlled antenna sites in Australia, Europe, and the U.S. could use single, larger antennas for uplink communications and arrays of small antennas for downlink communications.

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ABSTRACT | The current assets of the Deep Space Network (DSN) of the National Aeronautics and Space Administration (NASA), especially the 70-m antennas, are aging and becoming less reliable. Furthermore, they are expensive to operate and difficult to upgrade for operation at Ka-band (32[1] GHz). Replacing them with comparable monolithic large antennas would be expensive. On the other hand, implementation of similar high-sensitivity assets can be achieved economically using an array-based architecture, where sensitivity is measured by G/T, the ratio of antenna gain to system temperature. An array-based architecture would also provide flexibility in operations and allow for easy addition of more G/T whenever required. Therefore, an array-based plan of the next-generation DSN for NASA has been proposed. The DSN array would provide more flexible downlink capability compared to the current DSN for robust telemetry, tracking and command services to the space missions of NASA and its international partners in a cost-effective way. Instead of using the array as an element of the DSN and relying on the existing concept of operation, we explore a broader departure in establishing a more modern concept of operations to reduce the operations costs. This paper presents the array-based architecture for the next-generation DSN. It includes system block diagram, operations philosophy, user's view of operations, operations management, and logistics like maintenance philosophy and anomaly analysis and reporting. To develop the various required technologies and understand the logistics of building the array-based low-cost system, a breadboard array of three antennas has been built. This paper briefly describes the breadboard array system and its performance.

KEYWORDS | Antennas; array; deep-space network; low cost; space communications; telemetry; tracking

I. INTRODUCTION

The Deep Space Network (DSN) of the National Aeronautics and Space Administration (NASA) [1] currently uses 34-m and 70-m antennas for telemetry, tracking and command (TT&C) operations in support of deep-space missions. The oldest of these, the three 70-m antennas, provide the bulk of the ratio of antenna gain to system temperature (G/T) for the DSN. These were originally built in the 1960s and are becoming less reliable due to aging. These antennas and related systems are based on technologies many decades old and not well suited for modern handsoff automated remote, unattended operations, and therefore are more expensive to operate. Also, these antennas operate only up to X-band frequencies (8.4 GHz), where spectrum allocation limits bandwidth to a total of 50 MHz, which must be shared among multiple missions. For future space missions requiring larger bandwidths, it will be necessary to change to higher Ka-band frequencies, e.g., 26[2] or 32 GHz, where larger spectrum allocations are available for space communications. Upgrading the older assets would not be cost effective because they need costly upgrades for the extension of life, pointing performance, and surface accuracy required for the Ka-band operations. Furthermore,

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[1] 32 GHz is shorthand for the allocated 31.8–32.3 GHz.

[2] 26 GHz is shorthand for the allocated 25.5–27.0 GHz.

DSN needs assets that allow flexibility in operations (e.g., matching asset allocation to the G/T requirement of a mission), can be operated using a modern operations concept, and are capable of expansion as needs grow. Array-based architectures offer an attractive approach to a reliable, cost-effective, and flexible next-generation DSN.

The key implementation cost of arrays is expected to be the antenna mechanical systems—the cost is roughly proportional to $d^{2.7}$ [2], where d is antenna diameter. When the cost of the radio frequency (RF) and combining electronics is added, we find [3] that, for a fixed G/T, building an array of small-diameter antennas is more economical than building a large single antenna. Other benefits of arrays would be higher reliability (because the failure of any one of the antennas of an array would cause a degradation, not a failure of the communication link), the inherent flexibility in allocating required G/T, and the ease of planning maintenance and upgrade without substantial down time. Operational combining of signals from antennas (arraying) is routinely done for radio-astronomy arrays and was demonstrated for space communications in the mid-1980s (e.g., [4]). Operational arraying for telemetry was demonstrated in a DSN-VLA array in the late 1980s [5]. The Parkes-DSN array has been in place in the DSN since 1998 for downlink usage. Therefore, considering the advantages of arraying and demonstrated performance, we propose arraying of small antennas for future DSN downlink operations.

Section II describes the proposed approach and architecture of the system and Section III gives the block diagram of the array. Section IV describes the concept of operations (conops), user's view of operations, operations management and logistics, maintenance philosophy, and anomaly analysis and reporting for the DSN array. To develop various technologies required and understand the logistics of building a low-cost system, a breadboard-system array of three antennas has been built at the Jet Propulsion Laboratory (JPL), Pasadena, CA. The breadboard array and its performance are described in Section V. Section VI summarizes the current status and plans for the DSN array.

II. DSN ARRAY ARCHITECTURE

The architecture of the DSN array is shown in Fig. 1. We envision deployment in three sites at or near the longitudes of the existing DSN sites. DSN Array Central would be connected to the three regional array centers (RACs), one at each of the three longitudes. Each RAC would be connected to downlink and uplink antennas at the site at that longitude. Each site would have downlink antennas that could be arrayed to receive at X-band (8–8.8 GHz) and Ka-band (25–33 GHz) and uplink antennas with suitable transmitters for uplinks at 7.2 GHz band. Additional capabilities, e.g., TT&C capability at S-band (2.2 GHz), radar at X-band, and the receive capability at human exploration band near 37 GHz (37–38 GHz band), etc., can be added. The site would also include the electronics, signal processing, and facilities to support the DSN functions. Uplink and downlink antennas may be physically separated

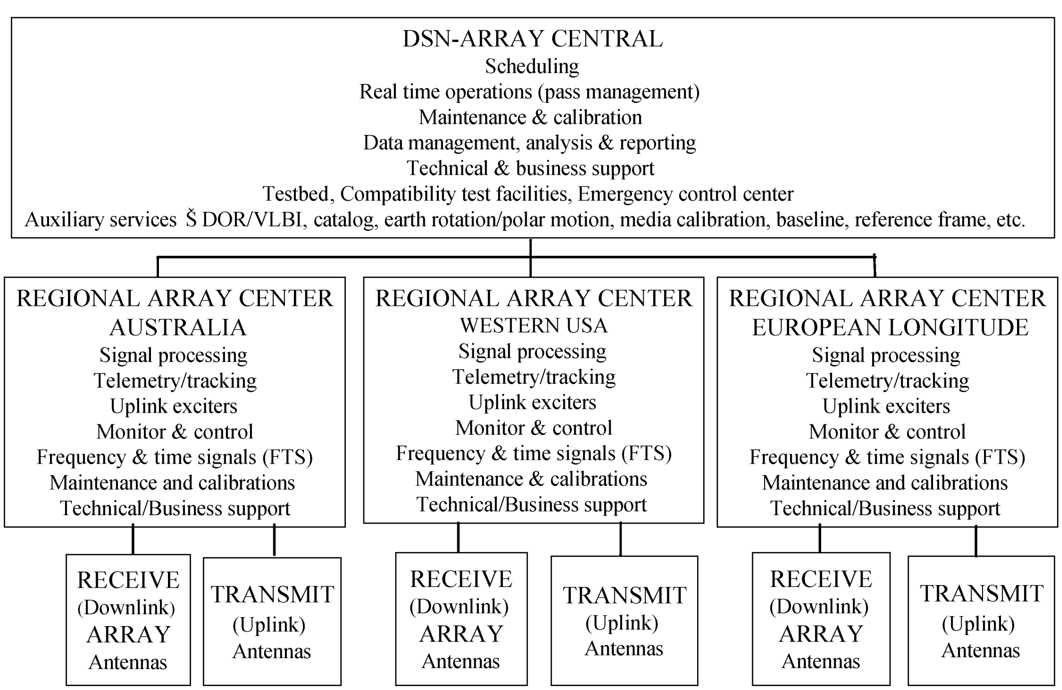

Fig. 1. ***DSN array architecture.***

to minimize radio frequency interference (RFI)—to avoid restricting front-end bandwidth needed for operations in some situations and useful for calibrations of the array, and regulatory concerns.

Site selection would consider multiple factors; key among them are the reuse of the existing sites (where significant infrastructure investments exist), effectiveness of Ka-band operations (Ka-band operation is more sensitive to adverse local weather), navigation performance (high-performance navigation requires East–West, as well as North–South, baselines), and the availability of land for possible future expansion.

The proposal envisions using arrays of small antennas for downlink and nonarrayed, larger, monolithic antennas for uplink. The proposed DSN array architecture and conops [6] allow for modular expansion of the downlink and/or uplink capabilities in terms of the number of antennas, supported frequencies, and specialized facilities (outrigger) to close coverage gaps in spatial (UV) domain and the ability to observe a spacecraft for given lower elevation limit on the observations. Partner sites may be used for such applications as additional support for spacecraft tracking or developing a catalog of calibration radio sources required for the differential one-way ranging and earth's polar motion, etc., needed for navigation applications. The DSN array would incorporate appropriate safety devices and procedures to ensure the equipment and operations do not pose a risk to the staff, public, equipment, or environment.

A. Regional Architecture

Each of the downlink antennas would have dual circular polarization at both X-band and Ka-band. Each antenna would produce two simultaneous intermediate frequency (IF) signals, having selectable polarization and frequency band, each with up to 500 MHz bandwidth. The IF signals from all antennas in a cluster would be brought together to the nearby control building for further signal processing. The signal processing equipment for each site would produce up to 16 phased array signals of up to 500 MHz bandwidth each. The phased array IF signals would be routed by monitor and control (M&C) for extracting telemetry and radiometric data by DSN or commercial telemetry processing equipment to produce telemetry data in Consultative Committee for Space Data System or other desired format. The IF signals may also be routed to other special processing equipment for other applications like generation of tracking data using very long baseline interferometry information for navigation applications. There may be further arraying of symbol streams between sites, if required. There would also be a correlation capability to measure autocorrelation and cross-correlations between IF signals from individual antennas over any part of the signal with bandwidth ranging from 125 kHz to 512 MHz. The correlation measurements would be used for calibration of the array and diagnosis of system problems to support smooth operations. It may enable use of the array to conduct an emergency search for a "lost" spacecraft.

III. SYSTEM BLOCK DIAGRAM

A block diagram of the proposed DSN array elements is shown in Fig. 2. The elements are as follows.

1) *Receive Array:* Array of small receive antennas with X-band (8.0–8.8 GHz) and Ka-band (25.5–33.3 GHz); an upgrade or augmentation to the 37–41 GHz band is not precluded by the initial design.
2) *Transmit Antennas:* nominally individual, larger antennas with suitable transmitters on each. Techniques for uplink arraying are being investigated and would be deployed if proven operationally feasible and cost effective.
3) *Frequency and Timing Signal (FTS):* frequency standards, reference frequency, and time signal distribution.
4) *Telemetry, Tracking, and Command:* produce telemetry data, radiometric products required for tracking, and radiating command signals to spacecrafts.
5) *M&C:* online and offline control of the system and associated management tools.
6) *Information Technology Infrastructure:* all computers, data transmission and storage and management.
7) *Facilities:* support infrastructure.
8) *Operations:* array operations and management.

IV. OPERATIONS CONCEPT

The basic components of the proposed DSN array support would be based on links and passes, as in the current DSN. A pass is a continuous period of support for a single mission or multiple missions (e.g., multiple spacecraft per antenna beam). Each pass contains periods of setup and teardown before and after the actual tracking support. A link is defined as the logical aggregation of assets, for a pass. A link would consist of some dedicated assets (antennas, arraying equipment, transmitters, and telemetry equipment) and portions of shared assets (frequency and timing, communications lines, switching equipment). The link gets formed in the beginning of a pass, from assets in a general pool, and dissolved after the pass, returning the assets to the general pool. A link can include assets in a single region or multiple regions.

Automation and Staffing: The DSN array would not be operated as an unattended ("lights out") network—the complexity of space operations and the uniqueness of each mission do not allow such a capability to be cost-effective. Instead, the conops would be based on managing the real-time operations with a small number of round-the-clock (24×7) personnel at DSN Array Central (nominally in

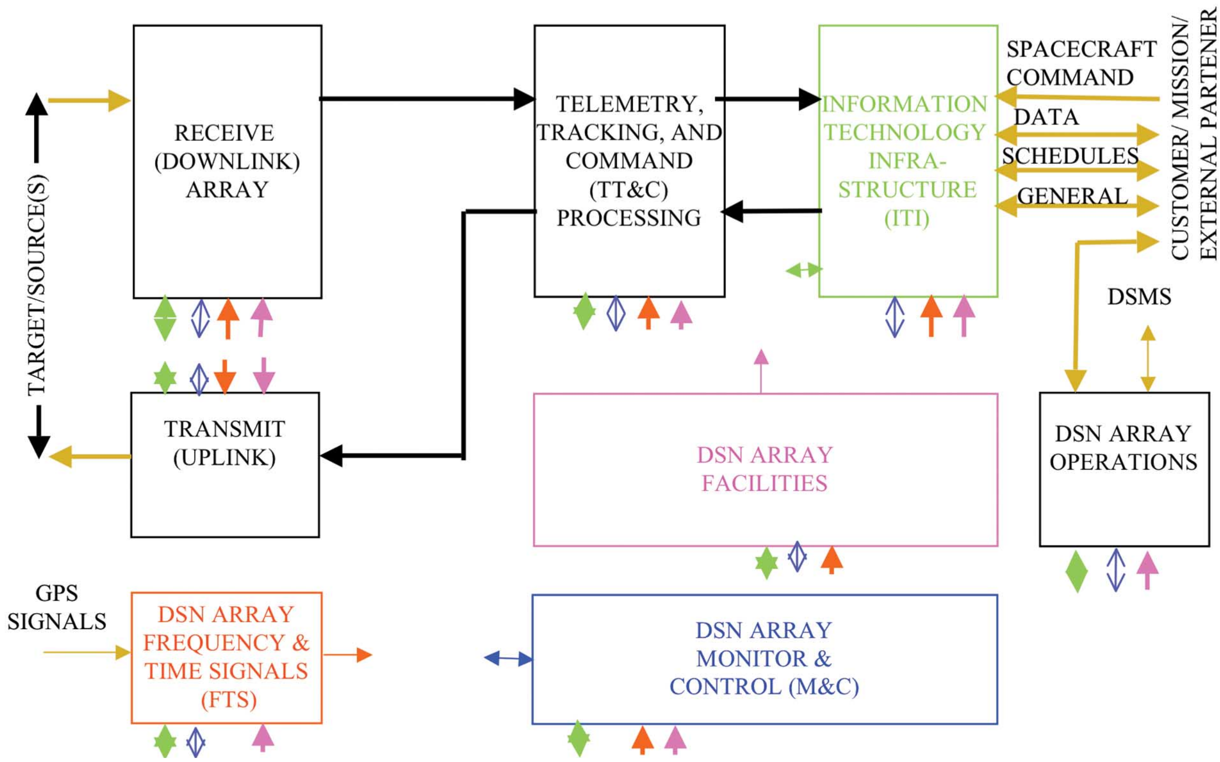

Fig. 2. ***Proposed DSN-array system block diagram.***

Pasadena). "Automation" would focus on providing tools for operations that would handle, without human intervention, nominal operations and selected nonnominal failures and free the 24 × 7 staff to attend to nonroutine events and intervene in routine operations, if needed. RACs may have two 24 × 7 persons, called rovers, for light repairs to meet reliability requirements and provide physical security.

Real-time operations at DSN Array Central would be staffed by a small number (about five) of 24 × 7 operators. The passes would be run from a schedule, and the users would be responsible for providing correct inputs for a pass, via proper mission parameter files (MPFs). For each site there would be about 50 full-time equivalent (FTE) 40 h a week (8 × 5) staff to perform all maintenance on the downlink antennas, uplink antennas, and other equipment. Independent estimates of work-hours by contracting consultants suggest that this level of support would be adequate. These staff would handle the logistics and perform first level of failure analysis and corrective actions. DSN Array Central non-real-time operations would be staffed by approximately forty 8 × 5 FTEs who would conduct user interfaces, handle logistics, and perform analysis, as needed.

DSN Array Central would be supported by an engineering organization that has the ultimate expertise in equipment details. In addition to designing and deploying new equipment, this staff would support the staff at the sites and oversee closure of the failure/anomaly reports (FARs) or any analysis of FARs.

Antenna as Least Replaceable Element (LRE): The DSN array would, to the extent possible, treat an antenna as the LRE. If the antenna becomes unusable during a pass due to a mechanical or electronic component problem (and cannot be restored quickly to service), the support would continue with the remaining antennas, if the margin allows, or another antenna would be brought into service. The fault isolation and restoration would be deferred to the next 8 × 5 shift. The antenna allocation process would include provision to add reserve capacity consistent with the criticality of the supported event. Based on a reliability analysis conducted by an independent contractor, the DSN Array scheduling process would reserve 5% of assets for routine maintenance and testing or other nonoperational support and is expected to provide better than 98.5% equipment reliability.

Real Time Operations: The DSN Array Central would oversee the real-time operations of the assets at the three sites. In general, the generation of TT&C products (e.g., frames for telemetry, radiometric observables for tracking) would be script- and schedule-driven, minimizing the need for human intervention. The operators at the DSN Array Central would oversee all processing including at the RACs and would intervene only during anomalies or when an override is required. Where practical, processing would be conducted at the RAC. Processing at DSN Array Central would occur only in cases involving multiple-site participation.

Non-Real-Time Operations: Most routine non-real-time operations would be controlled by software/scripts. Functions to be performed by the 24 × 7 and 8 × 5 staff are:

- priority and array time allocation;
- resource allocation and scheduling;
- validation of user provided MPFs;
- generation of observation control files (OCFs);
- addition of pre- and postpass calibrations;
- instrument calibrations and routine test observations;
- maintenance of calibration catalogs and tables;
- maintenance planning;
- data calibration;
- data quality analysis.

User's View of Operations: The DSN array resource allocation and scheduling process would be automatic based on prior approved algorithms and priorities. A user would provide a mission parameter file that would be used with a resource allocation file (RAF) generated by scheduling tools to produce an observation control file. The OCF would be used to execute a pass. Users would have access to monitor data for their pass and may update a MPF during a pass. However, updating the MPF during a pass may result in data discontinuity and/or loss of data. While the nominal user interface is via validated MPF files, the DSN array operations staff would be available to support the users as needs arise (e.g., "friend of the telescope"). After the pass, users would get a pass report accounting for the actual performance as evaluated by the DSN array. Users would also be encouraged to provide feedback to the DSN array, as soon as practical, about any discrepancies they identified in the pass results.

A. Maintenance Philosophy

To the extent possible, the DSN Array would use the fact that there are a large number of identical antennas (of size probably about 12-m diameter) to simplify maintenance. This would allow the DSN to largely decouple maintenance from operational commitments. The technical staff at DSN Array Central and at the RACs would work 8 × 5 during normal operations. The key roles of the staff at a RAC would be maintenance and repair of hardware and the initial disposition of the FARs. They would have access to monitor data, test tools, and suitable checking algorithms to support these roles. They would also conduct array calibration and diagnostic observations periodically or as needed to pinpoint problems. The DSN array would use a single FAR processing and tracking system to capture failures, anomalies, or other issues/concerns. FARs would be tracked, with access via secure internet, and closed via repair of hardware or new hardware design, new software, updated procedures or documents, or by acknowledging that the root cause is outside DSN array control (e.g., weather, radio frequency interference, or spacecraft events).

V. BREADBOARD ARRAY

The breadboard array was built to develop technologies and understand the logistics and methodologies required for minimizing the lifecycle cost of the DSN array. The approach was to develop technologies critical for the design and operations of the DSN array and gain experience for making decisions about critical-design issues and large dollar value systems/items. Analysis of the cost of building an array shows cost is minimized when the cost of antennas is roughly equal to the cost of the electronics and that total cost is minimized for antennas with diameters in the range of 10–20 m [3]. Recent industry-driven technological advances in electronics, like integration of microwave systems using low-noise monolithic microwave integrated circuits and digital signal processing, have reduced the cost of building reliable systems but minimally affected antenna costs. Therefore, a major uncertainty in the cost of building and operating the array is in antennas. Developing a low-cost and reliable antenna operating at Ka-band with a long lifetime and reliable operations was therefore one of the drivers for building the breadboard array.

The breadboard array, which is located at JPL in Pasadena, CA, consists of two 6-m diameter parabolic dishes using a hydroformed cell as primary reflector and a 12-m diameter parabolic dish using conventional panel design as primary reflector. The primary surfaces for both 6- and 12-m antennas are shaped to maximize the G/T performance [7], [8]. The two 6-m antennas are separated by about 30 m and located about 0.5 km from the 12-m antenna. A block diagram of the breadboard array is shown in Fig. 3.

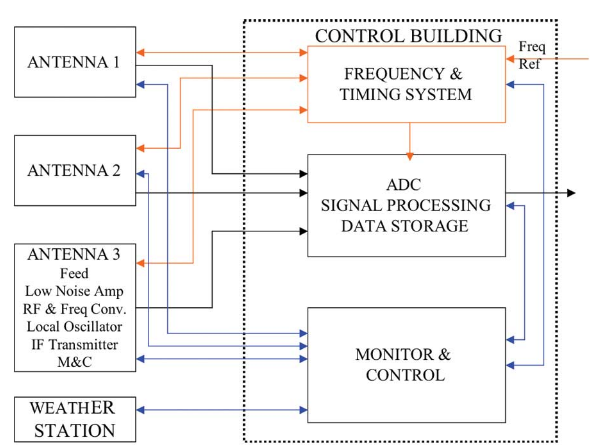

Fig. 3. ***A simplified block diagram of the breadboard array.***

Front-end electronics of the antennas consists of X-band and Ka-band cryogenically cooled feed and low-noise amplifiers providing simultaneous dual circular polarized signals at X- and Ka-bands. These signals are downconverted to IF in the range of 640–1280 MHz using a coherent local oscillator distribution system to all array elements. The local oscillator distribution system also includes round-trip path length measurements for the local oscillator fiber-optics path. Two of the four IF signals are transported to the central control building using optical fibers in the same bundle to each antenna as the optical fiber for the local oscillator signals. At the central building, the received IF signals are digitized at 1280 MSamples/s using 8-bit digitizers and given to a digital signal processing system [9] and built using field-programmable gate arrays (FPGAs). The digital signal processing uses architecture that converts signals from time domain to frequency domain (X-F); after processing, the signals are converted back to time domain, and therefore we call it X-F-X architecture. It compensates for path-length changes due to earth rotation in each signal path, corrects for any (differential) instrumental path delays, and performs cross-correlation between the signals from the antennas. The FPGAs are also being programmed to combine signals from the antennas after aligning phases for the signals from various antennas being combined instead of cross-correlating the signals from various antennas. The cross-correlation is performed on 2-bit quantized signals and signal combining is done using the 8-bit quantized signals.

Performance: System performance, system noise temperatures, and single-dish antenna efficiencies for the three antennas were measured using celestial radio sources Cassiopeia-A, Cygnus-A, and Taurus-A at 8.4 GHz (X-band) and Jupiter and Venus at 32 GHz (Ka-band). Expected antenna efficiency, system temperature [7], [8], and measured values are given in Table 1. Measured-system temperatures are in the range of 22–26 K at X-band and 32–45 K at Ka-band at zenith in clear weather conditions in Pasadena.

The 6-m antennas provide about 65% antenna efficiency at X-band and about 54% efficiency at Ka-band. The 12-m antenna has about 70% efficiency at X-band, close to what is expected. The signal processing system has been successfully used to measure correlated signals from celestial radio sources in spectral line mode for all three baselines at both X- and Ka-bands. Work on evaluating the 12-m antenna performance at Ka-band and suitability of the antennas and electronics for arraying and more work to understand the system performance is currently in progress. The present 12-m antenna promises to be much cheaper than conventional antennas of similar size working at Ka-band, though its daytime Ka-band performance seems to vary considerably, perhaps due to thermal changes.

Table 1 System Temperature (T_{sys}) at Zenith and Antenna Efficiency (A_e) Performance—Expected and Measured

	6m Antennas		12m Antenna	
Parameter	Expect	Measure	Expect	Measure
X-band T_{sys} (K)	17-25	24+/-2	14 -22	24
X-band A_e (%)	65-69	65	74-79	70+/-2
Ka-band T_{sys}(K)	31-45	35+/-3	31-45	44
Ka-band A_e (%)	55-58	53+/-3	61-65	

VI. SUMMARY

The proposed architecture and implementation plans for an array-based DSN, backed by analysis and successful risk-reducing demonstration, offer a future DSN that is cost-effective, highly reliable, and evolvable to meet NASA's emerging needs. The plans have been incorporated into the recommendations of the NASA Space Communications Architecture Working Group and are being considered for implementation. The breadboard array is working, and its performance is close to what was expected in most aspects except for the 12-m antenna's Ka-band performance during the day. We are currently trying to understand factors affecting it. ■

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